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Testing Technicolor with Scalars at the First Muon Collider¹

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Abstract. An interesting class of models of dynamical electroweak symmetry breaking allows only the third generation fermions to acquire dynamical masses, such that the masses of the first two generations should be given by coupling to a nonstandard “Higgs” doublet. The scalars in this case have large couplings to the second generation, so that they are copiously produced at a muon collider. We analyze the potential for discovery of the neutral scalars in the s -channel, and we show that at resonance there will be observed in excess of 10^5 events per year.

INTRODUCTION

Although the electroweak symmetry breaking and the quark and lepton spectrum may have a common origin, it is quite possible that they are generated by some new physics which manifests itself at low energy as distinct sectors. For example, the effective theory at a scale of order 1 TeV can include a sector that gives rise to the masses of the W , Z and third generation fermions, as well as a sector responsible for the masses of the lighter fermions.

This is the case when the electroweak symmetry is broken dynamically by some new strong gauge interactions, and only the third generation quarks and leptons couple to the fields charged under these interactions. In the context of technicolor models, this situation is discussed in [1,2]. The minimal mechanism for producing the masses of the first two generations requires a weak-doublet scalar transforming as the Higgs doublet, but having a positive squared-mass, as in the technicolor models with a scalar [3,4] or in bosonic technicolor models [5,6].

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By coupling to the dynamical symmetry breaking sector, the scalar acquires a small vacuum expectation value (VEV). The existence of the scalars is not troublesome as long as the theory described here is the low energy manifestation of a TeV scale theory which includes scalar compositeness or softly broken supersymmetry.

Because the VEV of the weak-doublet scalar is smaller than the electroweak scale, the Yukawa couplings of the “nonstandard-Higgs” bosons to the first and second generations must be larger than in the standard model. This is relevant for future collider searches. In particular, since these Yukawa couplings are proportional to the fermion mass, the s -channel production is very large at a muon collider.

Here we discuss briefly the discovery potential and resonant production of the “nonstandard-Higgs” bosons at a First Muon Collider, operating at a center of mass energy of up to 500 GeV. A comprehensive study of the collider phenomenology of the “nonstandard-Higgs” will be given elsewhere [7].

TECHNICOLOR WITH SCALARS

We assume that the electroweak symmetry breaking and the third generation fermion masses have a dynamical origin. To be specific, we consider a technicolor model constructed along the lines of ref. [2]. The second and first generation fermions acquire masses by coupling to a scalar, ϕ , which transforms under the gauge group like the standard model Higgs doublet.

In addition to the standard model fermions, consider one doublet of technifermions, P and N , and three scalars, ω , χ and ϕ , which transform under the $SU(4)_{\text{TC}} \times SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge group as:

$$\begin{aligned} \Psi_R &= \begin{pmatrix} P_R \\ N_R \end{pmatrix} : (4, 1, 2)_0, \quad P_L : (4, 1, 1)_{+1}, \quad N_L : (4, 1, 1)_{-1}, \\ \omega &: (4, \bar{3}, 1)_{-\frac{1}{3}}, \quad \chi : (4, 1, 1)_{+1}, \quad \phi : (1, 1, 2)_{+1}. \end{aligned} \quad (1)$$

The most general Yukawa interactions of ω and χ include only terms linear in the quark or lepton fields, such that there is a particular eigenstate basis in which only the third generation couples to the technicolored fields:

$$\mathcal{L}_Y^{\omega, \chi} = C_q \bar{\Psi}_R q_L^3 \omega + C_t \bar{t}_R P_L \omega^\dagger + C_b \bar{b}_R N_L \omega^\dagger + C_l \bar{\Psi}_R l_L^3 \chi + C_\tau \bar{\tau}_R N_L \chi^\dagger + \text{h.c.} \quad (2)$$

Using a phase redefinition on the third generation fields, $q_L^3, t_R, b_R, l_L^3, \tau_R$, we can choose the Yukawa coupling constants, $C_q, C_t, C_b, C_l, C_\tau$, to be positive.

We assume that the ω and χ techniscalars are sufficiently heavy to be integrated out, such that their effects in the low energy theory are given by four-fermion operators involving two technifermions and two fermions of the

third generation. As in QCD, the $SU(4)_{TC}$ technicolor interactions trigger the formation of technifermion condensates,

$$\langle \bar{P}P \rangle \approx \langle \bar{N}N \rangle \approx 2\sqrt{3}\pi f^3, \quad (3)$$

which breaks the electroweak symmetry at a scale f . This also results in masses for the t , b and τ [1,2]:

$$\begin{aligned} m_t &\approx \frac{\sqrt{3}}{2} \frac{C_q C_t}{M_\omega^2} \pi f^3, \\ \frac{m_b}{m_t} &= \frac{C_b}{C_t}, \\ \frac{m_\tau}{m_t} &= \frac{C_\tau C_l}{C_t C_q} \left(\frac{M_\omega}{M_\chi} \right)^2. \end{aligned} \quad (4)$$

The ϕ has Yukawa couplings to the standard fermions (these are similar with the standard model couplings of the Higgs doublet, but with different coupling constants), and also to the technifermions:

$$\begin{aligned} \mathcal{L}_Y^\phi &= \lambda_{jk}^e \bar{l}_L^j e_R^k \phi + \lambda_{jk}^u \bar{q}_L^j u_R^k i\tau^2 \phi^\dagger + \lambda_{jk}^d \bar{q}_L^j d_R^k \phi \\ &+ \lambda_+ \bar{\Psi}_L P_R i\tau^2 \phi^\dagger + \lambda_- \bar{\Psi}_L N_R \phi + \text{h.c.} \end{aligned} \quad (5)$$

where $i, j = 1, 2, 3$ are generational indices, and the λ 's are coupling constants. We consider the case where ϕ has a positive squared-mass, $M_\phi^2 > 0$, so in contrast to the standard model, the ϕ sector does not induce a VEV by itself. However, when the technifermions condense, the last two terms in the above Lagrangian give rise to tadpole terms, such that ϕ develops a VEV whose magnitude is [3,4]

$$\frac{f'}{\sqrt{2}} \approx (\lambda_+ + \lambda_-) \frac{2\sqrt{3}\pi f^3}{M_\phi^2}. \quad (6)$$

Note that we neglected a possible quartic term in the ϕ potential. If the high energy theory that accounts for the existence of ϕ turns out to produce such a quartic term (and possibly higher dimensional terms), then its effects can be easily included. The observed W and Z masses require

$$f^2 + f'^2 = v^2 \approx (246 \text{ GeV})^2. \quad (7)$$

The first three terms of \mathcal{L}_Y^ϕ are responsible for the masses of the quarks and leptons of the first two generations, and for the CKM elements.

The effective theory below a scale of order 1 TeV where the technicolored fields are integrated out includes only the standard fermions and gauge bosons,

an iso-triplet of Nambu-Goldstone bosons, π^a , $a = 1, 2, 3$, associated with the chiral symmetry breaking of the technifermions, and the components of ϕ [we assume $M_\phi \lesssim 1$ TeV, although eq. (6) does not exclude multi-TeV values]. ϕ decomposes into an iso-singlet σ , and an iso-triplet π'^a :

$$\phi = \frac{1}{\sqrt{2}} e^{-i\pi'^a \tau^a / f'} \begin{pmatrix} 0 \\ \sigma + f' \end{pmatrix}. \quad (8)$$

The triplets π^a and π'^a mix and give rise to the longitudinal W and Z , and to a triplet of physical pseudo-scalars. However, the large top mass suggests that $f \approx v$, so that

$$f' \ll f, \quad (9)$$

which implies that the mixing is small, and we will neglect it. Another consequence of inequality (9) is that

$$\lambda_+ + \lambda_- \ll \frac{1}{2\pi\sqrt{6}} \left(\frac{M_\phi}{f} \right)^2. \quad (10)$$

In this situation, the neutral real scalars σ and π'^3 , and the charged scalars, $\pi'^{\pm} = (\pi'^1 \mp i\pi'^2)/\sqrt{2}$, are almost degenerate, with a mass M_ϕ . The splittings in their masses are of order $(f'/f)^2$ and $\lambda_{\pm}^2 (M_\phi/f)^2$.

SIGNALS AT THE FIRST MUON COLLIDER

If the model presented in the previous section is indeed the correct description of physics up to a TeV scale, then the only direct discovery accessible at a $\mu^+\mu^-$ collider with \sqrt{s} below the first technihadron resonance will be the existence of the components of the ϕ doublet. Furthermore, for $M_\phi < \sqrt{s} < 2M_\phi$, only the neutral scalars, σ and π'^3 , can be produced.

The couplings of σ and π'^3 to quarks and leptons are in general flavor non-diagonal. However, because the off-diagonal couplings are constrained by flavor-changing neutral current measurements, we are going to consider only the flavor-diagonal couplings. These are proportional with the corresponding fermion masses in the case of the first two generations. The couplings to the third generation are more arbitrary, because they are proportional only with the small contributions to the fermion mass, δm_f with $f = t, b, \tau$, from the ϕ VEV.

Since the bulk of electroweak symmetry breaking is provided by the technicolor sector, the couplings of the neutral scalars, σ and π'^3 , to W^+W^- and ZZ are smaller by a factor of v/f' than the corresponding standard model couplings of the Higgs boson. On the contrary, the couplings of σ and π'^3 , to the fermions of the second and first generations are enhanced by a factor of

v/f' compared to the standard model Higgs boson. The couplings to the third generation are also enhanced by v/f' , but they are suppressed by $m_f/\delta m_f$.

The total decay widths of the σ and π'^3 scalars are equal, and given by

$$\Gamma \approx \frac{M_\phi}{8\pi f'^2} \left[3m_c^2 + 3m_s^2 + m_\mu^2 + 3(\delta m_t)^2 \left(1 - \frac{4m_t^2}{M_\phi^2} \right)^{1/2} \theta(M_\phi - 2m_t) \right. \\ \left. + 3(\delta m_b)^2 + (\delta m_\tau)^2 \right] + \Gamma(W^+W^- + ZZ) . \quad (11)$$

We take the VEV of ϕ in the range

$$1 \text{ GeV} \lesssim f' \lesssim 10 \text{ GeV} , \quad (12)$$

where the lower bound is chosen to avoid Yukawa coupling constants larger than order one, and the upper bound is chosen to satisfy condition (9). In this case, the width for scalar decay into pairs of gauge bosons, $\Gamma(W^+W^- + ZZ)$, is at most a few percent of the width for $\sigma, \pi'^3 \rightarrow c\bar{c}$, and we neglect it. Generically, there is no reason to expect that δm_f is larger than the corresponding second generation mass. For simplicity we assume $(\delta m_f)^2 \ll m_c^2$, such that the width of the σ and π'^3 scalars is dominated only by the $c\bar{c}$ final state:

$$\Gamma \approx \frac{3m_c^2 M_\phi}{8\pi f'^2} \approx 13.2 \text{ GeV} \left(\frac{3 \text{ GeV}}{f'} \right)^2 \left(\frac{M_\phi}{500 \text{ GeV}} \right) . \quad (13)$$

Given the enhanced couplings to the second generation, the s -channel production of the neutral scalars at a $\mu^+\mu^-$ collider is large. The natural spread in the muon collider beam energy, $\sigma_{\sqrt{s}}$, is much smaller than Γ , and can be ignored in computing the effective s -channel resonance cross section [8]:

$$\bar{\sigma}(\mu^+\mu^- \rightarrow \sigma, \pi'^3 \rightarrow X) \approx \frac{4\pi\Gamma^2}{(s - M_\phi^2)^2 + M_\phi^2\Gamma^2} \\ \times B(\sigma, \pi'^3 \rightarrow \mu^+\mu^-) B(\sigma, \pi'^3 \rightarrow X) . \quad (14)$$

We are interested especially in the case where the final state is $X \equiv c\bar{c}$. The branching fractions for the decays into a pair of muons, respectively into c -quarks, are given by

$$B(\sigma, \pi'^3 \rightarrow \mu^+\mu^-) \approx \frac{m_\mu^2}{3m_c^2} \approx 0.2\% \\ B(\sigma, \pi'^3 \rightarrow c\bar{c}) \approx 1 - \frac{m_s^2}{3m_c^2} - \dots \quad (15)$$

where the ellipsis stands mainly for the branching fractions into W^+W^- , ZZ , $\mu^+\mu^-$, etc. Therefore,

$$\bar{\sigma}(\mu^+\mu^- \rightarrow \sigma, \pi'^3 \rightarrow c\bar{c}) \approx \frac{8\pi\Gamma^2}{(s - M_\phi^2)^2 + M_\phi^2\Gamma^2} \left(\frac{m_\mu^2}{3m_c^2} \right). \quad (16)$$

The main background comes from $\mu^+\mu^- \rightarrow \gamma^*, Z^* \rightarrow c\bar{c}$, and amounts to

$$\sigma_B(\mu^+\mu^- \rightarrow c\bar{c}) \approx 0.7 \text{ pb} \frac{(500 \text{ GeV})^2}{s}. \quad (17)$$

We first study the discovery potential of a $\mu^+\mu^-$ collider operating at a maximum center of mass energy of 500 GeV. The beam energy can be reduced at the expense of luminosity. A decrease in the beam energy by a factor of two leads to a decrease in luminosity by a factor of ten [9]. The number of scan points can be optimized as follows. Consider that the adjacent scan points are separated by an energy difference $x\Gamma$, implying that

$$\begin{aligned} \bar{\sigma}(\mu^+\mu^- \rightarrow \sigma, \pi'^3 \rightarrow c\bar{c}) &\geq \frac{8\pi}{(4x^2 + 1)M_\phi^2} \left(\frac{m_\mu^2}{3m_c^2} \right) \\ &\approx \frac{80 \text{ pb}}{4x^2 + 1} \left(\frac{500 \text{ GeV}}{M_\phi} \right)^2. \end{aligned} \quad (18)$$

To observe at a particular scan point with \sqrt{s} a number of $c\bar{c}$ final state events which is 5σ over the background requires an integrated luminosity

$$\begin{aligned} L(s) &\geq \frac{5\sigma_B(\mu^+\mu^- \rightarrow c\bar{c})}{r(c\bar{c})[\bar{\sigma}(\mu^+\mu^- \rightarrow \sigma, \pi'^3 \rightarrow c\bar{c})]^2} \\ &\approx \frac{5.6 \times 10^{-4} \text{ pb}^{-1}}{(500 \text{ GeV})^2} \frac{(4x^2 + 1)^2 M_\phi^2}{r(c\bar{c})s}, \end{aligned} \quad (19)$$

where $r(c\bar{c})$ is the efficiency for observing the $c\bar{c}$ final state, and is given basically by the square of the c -tagging efficiency. The integrated luminosity necessary for searching the scalar resonance over the whole range of beam energy is

$$\begin{aligned} L &= \frac{1}{x\Gamma} \int_{\sqrt{s}_{\min}}^{\sqrt{s}_{\max}} d(\sqrt{s}) L(s) \\ &\approx \frac{5.6 \times 10^{-4} \text{ pb}^{-1}}{(500 \text{ GeV})^2} \frac{(4x^2 + 1)^2 M_\phi^4}{r(c\bar{c})x\Gamma} \left(\frac{1}{\sqrt{s}_{\min}} - \frac{1}{\sqrt{s}_{\max}} \right). \end{aligned} \quad (20)$$

Clearly, x should be chosen to minimize L . At the minimum,

$$x = \frac{1}{2\sqrt{3}}, \quad (21)$$

which gives

$$L_{\min} = \frac{0.14 \text{ fb}^{-1}}{r(c\bar{c})} \left(\frac{f'}{3 \text{ GeV}} \right)^2 \left(\frac{M_\phi}{500 \text{ GeV}} \right)^3 \left(\frac{500 \text{ GeV}}{\sqrt{s}_{\min}} - \frac{500 \text{ GeV}}{\sqrt{s}_{\max}} \right). \quad (22)$$

For $\sqrt{s}_{\max} = 500 \text{ GeV}$, $\sqrt{s}_{\min} = 250 \text{ GeV}$, and $r(c\bar{c}) \approx 10\%$,

$$L_{\min} = 1.4 \text{ fb}^{-1} \left(\frac{f'}{3 \text{ GeV}} \right)^2 \left(\frac{M_\phi}{500 \text{ GeV}} \right)^3. \quad (23)$$

The peak luminosity assumed at this workshop is $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 500 \text{ GeV}$, which corresponds to roughly $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 250 \text{ GeV}$. Note that the average luminosity is significantly lower, $7 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 500 \text{ GeV}$, but given that the scalar resonance is broader than the spread in the beam energy, there is no need for a good energy resolution (the upper value given in [9], $\delta E/E = 0.12\%$, being sufficient), and therefore the peak luminosity can be used. This situation is in contrast with the search for a light standard model Higgs which is narrower than the spread in beam energy.

Eq. (23) shows that with a luminosity of order $100 \text{ fb}^{-1}/\text{year}$, the scalar resonance will be discovered in a short period of time, even for f' larger than 10 GeV .

Once the resonance is found, either at the muon collider by varying the beam energy, or at the LHC, the beam energy can be adjusted to the peak (even if this requires a significant reduction in the luminosity) and then the production cross section becomes very large:

$$\sigma(\mu^+\mu^- \rightarrow \sigma, \pi'^3 \rightarrow c\bar{c}) \approx 80 \text{ pb} \left(\frac{500 \text{ GeV}}{M_\phi} \right)^2. \quad (24)$$

With a luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ($7 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$), and a c -tagging efficiency of $\sim 30\%$, there are going to be observed approximately 10^6 (5×10^4) events per year. This will make possible precision measurements of the couplings and masses of the neutral “nonstandard-Higgs” bosons, which in turn will open a window towards the TeV scale physics.

It is remarkable that the peak cross section is independent of the ϕ VEV. This is a consequence of the small couplings of the ϕ to pairs of gauge bosons.

CONCLUSIONS

The large resonance cross section computed in section 3 warrants the label “nonstandard-Higgs factory” for the muon collider. On the other hand, if the class of dynamical electroweak symmetry breaking models discussed here is correct, and the ϕ mass turns out to be significantly larger than 500 GeV , then no discovery will be made at the First Muon Collider, and there is need for a higher-energy muon collider. As discussed repeatedly at this workshop, the 4

TeV muon collider would also be a great tool for studying the strong dynamics sector. We emphasize that a “nonstandard-Higgs” with large couplings to the second generation might also be necessary in models where the strong dynamics is different than technicolor, for example in models that incorporate the top condensation seesaw mechanism [10], or in models with discrete horizontal symmetries [6].

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